ON -LINE TOOL WEAR MONITORING IN TURNING USING FORCE RATIO

A Thesis Submitted
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by

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CERTIFICATE

It is certified that the work contained in the thesis entitled " ON-LINE TOOL WEAR MONITORING IN TURNING USING FORCE RATIO" by Mr. KOTA KRISHNA KISHORE, has been carried out under my supervision and this work has not been submitted elsewhere for a degree.

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Nomenclature

V : Cutting velocity.

f : Feed rate.

d : Depth of cut.

D : Diameter of the work piece.

h_f : The flank wear land

x_i : Input cutting parameters.

F : Force acting on the tool.

F_f : Feed Force.

F_c : Cutting Force.

F_r : Radial Force.

R : Resistance.

l : Length of the strain gauge wire.

P_c : Power required for cutting operation.

T : Tool life.

w : Tool wear.

$T_1, T_2, T_3, T_4, C_1, C_2, C_3$ and C_4 : Strain gauges.

Abstract

The automation and optimization of the manufacturing processes play an important role in improving productivity. Tool wear monitoring and its estimation are essential for improved productivity of manufacturing systems. Tool wear sensing plays an important role in the optimization of tool replacement during automated machining in flexible manufacturing systems. One of the most important techniques for automation of a manufacturing system, which should be developed at the current stage, is an on-line tool wear monitoring technique. The focus of this work is to develop a reliable method to predict flank wear during a turning process. The present work is dedicated to develop a mathematical model for on-line monitoring of tool wear in a turning process. Force signals are highly sensitive carriers of information about the machining process and they are hence, the best alternatives for tool wear monitoring. The research on tool wear monitoring has shown that there is a good correlation between the dynamic cutting force and the flank wear. Utilization of force signals to achieve on-line tool wear monitoring has been presented in this work. A mathematical model has been developed to describe the wear-force relationship for steady center lathe turning conditions. Such a model has been found to accurately represent the wear development. The relation between the flank wear and the ratio of force components is established based on data obtained from a series of experiments. The measurement of variation of the ratio between the feed and the cutting components (F_f/F_c) has been found to provide a practical method for an in-process approach to the quantification of tool wear and at the same time to eliminate the effect of variation in work piece hardness so that the proposed approach could be more universally implemented. A series of experiments were conducted to study the effects of tool wear as well as other cutting parameters on the cutting force signals and to establish a relationship between the force signals and the tool wear as well as other cutting parameters when turning C45 work material using an HSS tool. The flank wear and ratio of forces, at different working conditions are collected experimentally to develop a mathematical model for predicting the flank wear. The model is verified by comparing the experimental values with the predicted values. The relationship was then used for on-line tool flank wear monitoring.

Chapter 1

Introduction

1.1 Introduction

In recent years, many advances have been achieved in the automation of the cutting process. However, the development of a fully automated machining system is unrealizable until robust and practical methods are developed to sense the amount of tool wear on-line. Such a development would also enhance the quality of the product by ensuring that the surface and geometrical specifications are within the tolerance zone. In addition there would be possibilities of increased cutting speeds, leading to a decrease in cutting times, all of which could result in an estimated overall savings of up to 40% of the total machining cost. Tool wear is one of the important factors affecting production optimization. The complex stochastic nature of the tool wear is one of the obstacles in achieving manufacturing automation. Adaptive control of machine tools provides a way to meet the ultimate manufacturing targets. To take full advantage of this technology there should be an in-process tool wear monitoring technique. This technique requires a model to get the on-line values of difficult-to-measure parameters such as tool wear from easily measurable values like tool forces, cutting speed, feed, depth of cut, work piece diameter etc.

1.2 Tool wear and Sensing methods

The most undesirable yet inherent characteristic of the machining processes is wear of the cutting tool. In order to prevent further damage to machine or the high rough surface finish, the essential part of a machining system in an unmanned factory is the ability to replace tools automatically due to wear or damage. Most tools fail either from fracturing or gradual wear. However there are other types of wear contributing to the tool wear.

The various types of wear a cutting tool may be subjected to are illustrated in Fig.1.1. The failure of a cutting tool may be due to one or more of the following reasons [1]:

1. Plastic deformation of tool due to high temperature and large stresses.
2. Mechanical breakage of tool due to large forces and insufficient strength and toughness.
3. Blunting of the cutting edge of the tool through a process of gradual or progressive wearing action.

Out of the various types of tool wear, flank wear FW on the flank face and primary cutting edge along with its accompanying notch, N and crater wear on the rake face, CW are classified as regular types of tool wear due to their regular time-related growth characteristics. The other types of wear, termed as irregular types, can generally be avoided by proper selection of tool material and cutting conditions. But whatever be the cutting conditions, regular types of wear will always occur though at varying rates. Due to these reasons flank and crater wears have been the subject of most studies in the area of tool wear

Tool wear affects the behavior of the machine-tool-work piece system. So the tool wear sensor can detect signal from different parts of the system: directly from the tool or from the work piece or finally from the process (machine), continuously or intermittently. Tool wear sensing set up can be based on direct measurement methods or indirect measurement methods as suggested by Micheletti *et.al.,* [2]. Direct tool wear sensing aims at measuring the tool wear on the cutting edge. In this case the measuring device evaluates the

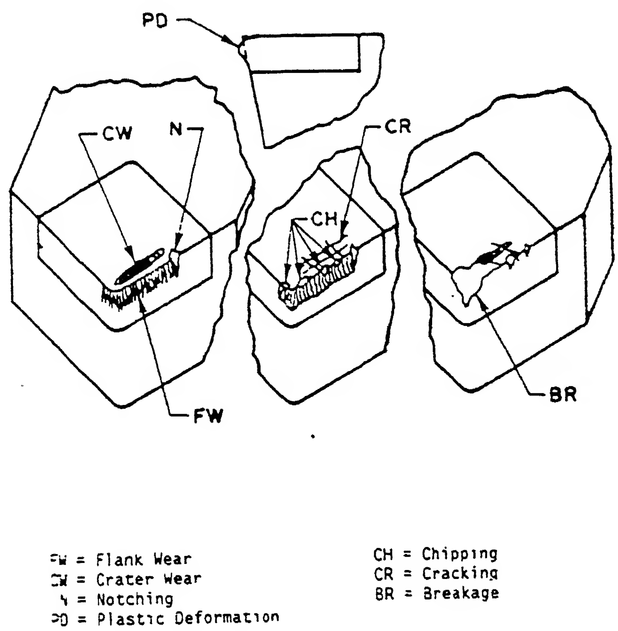

Figure 1.1: Different types of Tool Wear

volumetric loss from the tool due to the tool wear. Techniques using radio-isotopes as tracers; chemical analysis of tool particles carried by chip; electron probe microscope; weighing of tool before and after cutting etc. belong to this case. The measuring procedure can be any one of optical, electric, mechanical, pneumatic, acoustic, inductive or capacitive. The method of measurement may be with or without contact. These methods are very difficult (and some times impossible) to use on-line especially when there is a continuous contact between the tool and the work piece, like in turning, and are prone to errors because of complex nature of measurements. They are even inaccurate. Indirect methods are directed towards measuring some process variables and relating them to the tool wear. Enough work had been done to correlate the motor power, torque or the electric current with the tool wear by many investigators. But some limitations and draw-backs have been reported. Due to difficulties already mentioned in using direct measurement methods, especially on work shop floor, many researchers have been made trying to find out possibilities to measure other parameters, closely correlated with the tool wear. The proposed parameters are:

1. Cutting forces and/or torque

2. Vibrations and sonic analysis (noise)
3. Roughness of machined surface
4. Work piece dimension change
5. Relative position between the tool and the work piece.
6. Temperature and thermoelectric effects
7. Energy input to the system

1.3 Literature Review

Enough work had been done by previous researchers to correlate these parameters with the tool wear progress. Koren *et.al.*,[3] proposed a model-based approach to on-line tool wear and breakage detection. A model-based approach is considered important for machining under variable cutting conditions, and for use with adaptive control systems that automatically adjusts the feed rates. The basic approach has been developed and illustrated with a simple simulation model. The simulation results confirm the feasibility of the proposed model-based approach and indicate the need for further research to obtain experimental confirmation. They felt that further research was desirable on process modeling, estimation algorithms and on-line training of the model-based approach by using artificial intelligence methods.

S.K.Choudhury and S.Ramesh [4] used an optical displacement sensor for on-line monitoring of tool wear. The width of nose wear-land has been measured with the help of a shadowgraph and compared with that obtained from the sensor output. A feed-back-control system to provide compensation for the tool wear to keep the dimensions of the work piece within the tolerance limit has also been developed.

S.B.Rao [5] developed a microcomputer based technique for monitoring the flank wear on a single point tool engaged in turning operation. The technique is based on the real time computation of a wear index (**WI**). The **WI** is a measure of the resistance at the tool tip-work piece interface along the flank, to the forced oscillations of the cantilever

portion of the tool holder, during machining. Increasing flank wear results in an increasing area of contact between the tool tip and the work piece. This translates to an increasing **WI**, proportional to flank wear-land width and independent of the other cutting process variables. This **WI**, which can be computed on-line as a ratio of the measured dynamic force amplitude to the vibration amplitude, at the first natural frequency of the cantilever portion of the toolholder, forms the basis of the microcomputer system.

Realizing from the literature on metal turning the strong interrelationship between a changing force spectrum and tool wear, a theoretical model was presented by Akgerman [6] which relates the wear on flank and rake faces of tool tip to the cutting force vectors and the changing depth of cut on the work piece. These essential linear relationships have been experimentally verified. The theoretical model was developed in two sections. The first section deals with the expected geometry caused by the wear considering lost rake face area and decrease in uncut chip cross-section. The second section deals with the observed variations in cutting force, F_c and their relationship to both the decrease in uncut chip cross sectional area and the increase in flank wear land.

Danai *et.al.*, [7] proposed a dynamic state model of tool wear which is considered as the basis for an on-line tool wear sensing system. The model states include flank wear and crater wear, and the state equations are developed from the available relationships in the literature. This nonlinear state model provides qualitatively responsible results, and is linearized and analyzed about particular operating conditions. These linearized equations provide a model structure, which together with on-line parameter estimation techniques, could be used to develop an adaptive observer for the tool wear estimation.

A unique technique is developed by Kaye *et.al.*, [8] for on line prediction of tool flank wear in turning using the spindle speed change. A mathematical model is presented for the approach. The speed sensing element is an optical encoder mounted on the spindle shaft and interfaced to an IBM microcomputer employing custom designed electronics. The changes in spindle speed are compensated for lathe transmission ratio, electrical configuration of lathe motor, and the torque speed relationship of the machine. One of the most promising techniques for tool wear detection appears to be the measurement and use of cutting forces. Force signals are highly sensitive carriers of information about the machining process and they are hence, the best alternatives for tool wear monitoring. The three components of

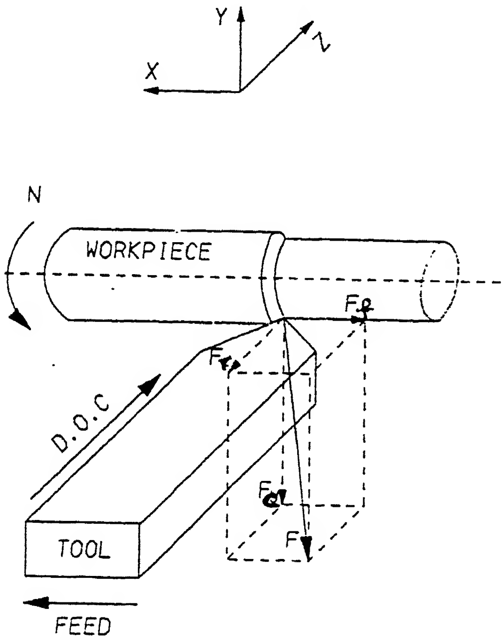

Figure 1.2: Cutting Force Components in Turning Operations

Even though it has been agreed among many investigators that the change of tool forces represents an accurate and reliable approach to assess tool wear and failure, disagreement still exists over the fact that which component is the most sensitive and reliable. In this study Force-Wear inter relationships are formulated for possible use for in-process tool wear monitoring through measurement of the variation in cutting forces. The use of force information in tracking the tool wear has been proposed and shown to be viable by a large number of researchers. Unfortunately such properties of work piece as hardness and diameter, which effect the tool wear significantly, were not taken in to account. Whereas the hardness often varies along the depth of the work piece, its diameter changes as the machining progresses.

G.Caprino *et.al.* [9] in his work concerning orthogonal cutting (milling) of unidirectional glass fiber-reinforced plastics by high speed steel tools concluded that both the horizontal and vertical forces undergo large variations with tool wear. However, some evidence exists that increase in horizontal force is strictly dependent on the variation of vertical force at the tool flank. On the contrary, the forces generated at the tool face appear to be substantially unaffected by the tool wear. A precise correlation seems to exist between the increase in vertical force at the tool flank and the flank wear. Therefore, it is expected that the dependence of this force on the wear-land can be analytically modeled.

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D.Cuppini *et.al.*, [10] focused on the methods and devices on in-process tool wear monitoring in turning operations. An approach to tool decay monitoring based on cutting power measurement has been presented. The implementation of a continuous monitoring method based on experimental relationships between the wear and the cutting power is described, which utilizes a power monitor device for sensing the total power required to drive the machine tool. A system performing an automatic tool replacement strategy, based on such indirect wear measurement, is presented and discussed with application on the shop floor. The relationship between the cutting power P_c and the tool wear w has been expressed by the following linear function.

$$P_c = 2.941w + 6.838 \tag{1.1}$$

From where,

$$w = 0.340P_c - 2.325 \tag{1.2}$$

But the important parameters like work piece properties, cutting speed, feed and depth of cut are not taken into account, which influence the tool wear by a large amount. This relationship does not seem to monitor the flank wear accurately.

I.Yellowley and C.T.Lai [11] suggested an approach that utilizes force ratios which are known to be relatively insensitive to wear in the identification of cutting conditions. The identified cutting conditions are then used, in a model of sharp tool forces to calculate the expected force ratio. A comparison of actual force ratio to that of calculated for a sharp tool is then used to infer the tool condition. However any direct relationship between tool wear and force ratios is not focused.

M.A.Elbestawi *et.al.*, [12] presented an approach for on-line monitoring of flank wear in milling. This approach is based on the variations of magnitude of cutting force harmonics with the flank wear. It is shown first, using computer simulations, that the sensitivity of the

magnitude of various harmonics in cutting force spectrum to flank wear, varies depending on the immersion ratio and the number of teeth in the cutter. The results of computer simulations were verified experimentally at various cutting conditions. An on-line monitoring strategy is then proposed which uses signature features selected from the harmonics of cutting force signals. Unfortunately no other cutting parameters are included in the process of monitoring and there is no relationship derived as well.

S.E.Oraby and D.R.Hayhurst [13] have developed mathematical models to describe wear-time and the wear-force relationships. Cutting forces have been found to correlate well with the tool wear progress and with tool failure. However, the wear-time models are generally incapable of estimating the wear level in the third stage at which a very high tool wear rate occurs. Moreover, random disturbances such as tool chipping and fracture are usually not detectable using this technique. In the wear-force models the use of ratio of feed force to cutting force is not studied. Moreover, the effect of the work piece properties on tool wear has not been given sufficient attention.

In the present work tool wear model as a function of force ratio, cutting speed, feed, depth of cut and diameter of the work piece is established using experimental data. Tool wear is then estimated by using this model. Finally, conclusions based on these results are made and scope for any future work is discussed.

1.4 Organization of Thesis

The organization of thesis is as follows:

- **Chapter 1** gives an introduction to the tool wear and sensing methods as well as a detailed literature review has been presented.
- **Chapter 2** discusses about the theoretical analysis.The wear phenomenon in turning is mentioned briefly. The equation is derived and solution for finding mathematical model is given.
- **Chapter 3** discusses the experimental set up, instrumentation, experimental procedure and the various cutting conditions employed.

- **Chapter 4** presents the experimental results and discusses the development and validation of the mathematical model.
- **Chapter 5** concludes the work and presents the scope for the future work.

Chapter 2

Theoretical Analysis

2.1 Tool Wear Phenomenon in Turning

Wear which is described as the total loss of weight of the sliding pairs accompanying friction, is classified in four basic classes.

Abrasion wear: It is due to ploughing by hard constituents including the fragments of the built-up-edge as they are swept over the tool surface.

Adhesion wear: When metallic surfaces are brought into intimate contact under moderate loads, a metallic bond between the adjoining materials takes place.

Diffusion wear: If the mechanical process involved in the adhesion is capable of increasing the localized temperature of the real area of contact of a surface, inter-facial diffusion will occur allowing a more intimate approach of the two surfaces. Wear at a higher cutting speeds is often attributed to the process of diffusion.

Chemical wear: It is due to interaction between the mating surfaces, in the presence of a fluid. If the fluid is active to the tool, wear rate may be accelerated by the chemical reaction. In the cutting operation with fluids, the chemical wear process may influence the tool-wear phenomenon and tool life.

Electrolytic wear: Electrolytic wear is the wear process which is due to possible galvanic corrosion between the tool and the work piece materials.

In metal cutting operation the cutting tool comes into contact with the chips and already machined work piece at high velocities. So there exists a friction between the tool and the other two elements. Gradually the tool wears out due to one or more of the above mentioned phenomena. Out of all the phenomena, three main forms of the progressive tool wear mechanisms were identified as adhesion, abrasion and diffusion wears. Adhesion and abrasion are macro-transfer type mechanical wear processes whereas diffusion is micro-transfer type thermo-mechanical process. When rubbing surfaces are free from any active chemical environment and the deteriorative action of *emf* is absent, the mechanical wear process contributes to the major share of the tool wear volume, particularly, at lower rubbing speeds

The various types of wear a single point tool may be subjected to are discussed briefly in **Chapter 1.** Types of wear observed specifically in single point cutting tools are shown in Fig 2.1.

In **turning** operation, because of the progressive or regular types of tool wear, one or more of the following four wear zones appear on the cutting tool [14] as shown in Fig 2.2.

- ► The **flank wear land** is more or less uniform on the flank face of the tool. Despite the relief angles provided on the flank face of the cutting tool, some amount of rubbing between this face and the finished work piece surface is always present forming the wear land. The width of the wear land is taken as the measure of the amount of flank wear.

- ► The **crater wear** is the dished-out section on the tool rake face and is formed due to high contact stress and high chip-tool interface temperatures. The crater depth is generally maximum at a distance from the cutting tip, and the crater curvature corresponds to the radius of the chip curvature. High speed cutting, leading to high temperatures, results in severe cratering. This eventually causes weakening of the tool edge and its fracture.

- ► The **nose wear** is formed at the nose radius and near the end relief face. The wear here

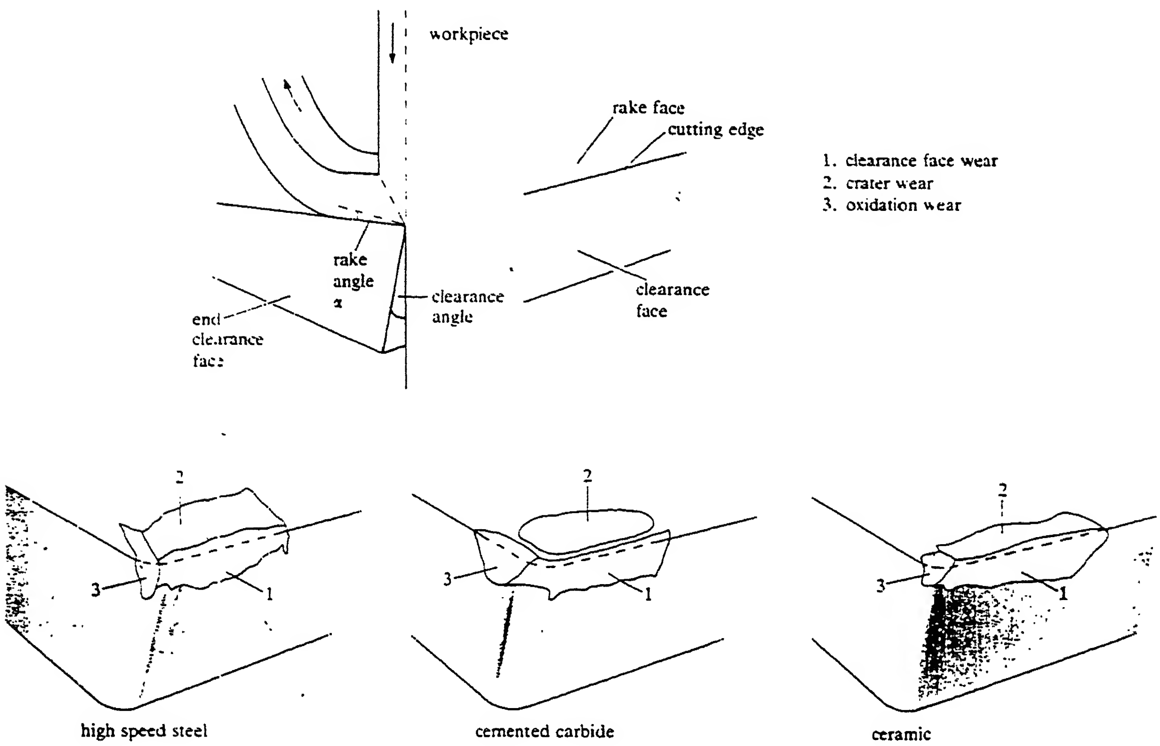

Figure 2.1: Types of wear in single point cutting tools

is partially in continuation of the wear land around the nose radius. This contributes to the increased roughness of finished part as the wear progresses.

- The **notch wear** is formed exactly at one end of width of cut where the major cutting edge starts penetrating into the work piece.

Analysis of cutting tool wear have traditionally emphasized flank wear more than crater wear and the reason is the more direct influence the flank wear has on the accuracy of the product. Among all the types of wear the flank wear and the resulting recession of the cutting edge affects the work piece dimension as well as quality to a large extent. The onset of crater wear results in:

- Change in mechanics of the cutting process (the effective rake angle and the chip tool

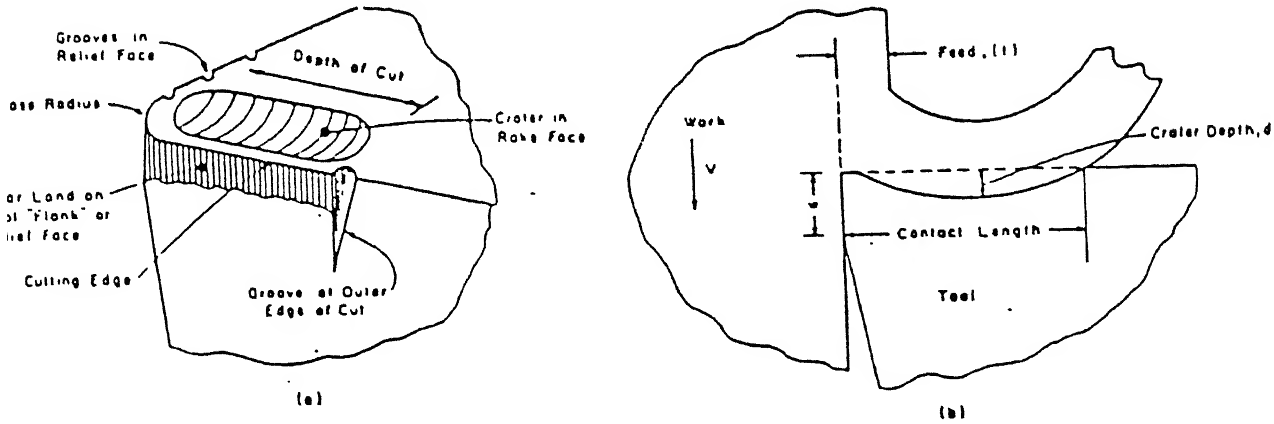

Figure 2.2: Geometry of Tool Wear

contact length change).

- ► Weakening of the tool.

Flank wear, on the other hand, has three fold influence [15]. It results in:

- ► Changes in mechanics of the cutting process.
- ► An increased tendency of chatter.
- ► Changes in dimension of the product.

That is why the single most significant type of wear that had drawn constant attention is flank wear. Thus the current analysis is restricted to the wear on the flank of the cutting tool.

2.2 Development of Mathematical Model

The most fundamental approach to the problem of tool wear has been to define a critical amount of flank wear-land. When this amount of wear is reached, it is assumed that the

tool has reached the end of its useful life. Since the rate of development of flank wear is a function of material properties and the cutting process variables, F.W.Taylor proposed the relationship as:

$$VT^n = C \tag{2.1}$$

Where, T = Tool life V = Cutting speed C, n = Constants depending on tool and work material, Tool geometry, and cutting conditions.

The relationship between the tool life T and the cutting variables as cutting speed, V, feed, f, and depth of cut, d, may take the form:

$$T = a_o V^{a_1} f^{a_2} d^{a_3} \tag{2.2}$$

Where, a_o, a_1, a_2 and a_3 are constants

This equation is some times called the extended Taylor's equation. There are various methods to determine the tool life data. If the wear-land is considered constant as suggested by Taylor.J (see Fig 2.3.) then the wear-land curves can be extrapolated to determine the time to failure (tool life), thus[16]

$$T = \frac{w_f - w^1}{k_w} \tag{2.3}$$

Where, w_f is the wear-land failure criterion, w^1 is the wear-land intercept, found experimentally, k_w is the wear-land growth rate, equal to slope in Fig 2.3 and T is the tool life for given cutting conditions.

The tool wear at time t can be expressed as

$$w = w_o + mt \tag{2.4}$$

or

$$w = w_o + \Delta w \tag{2.5}$$

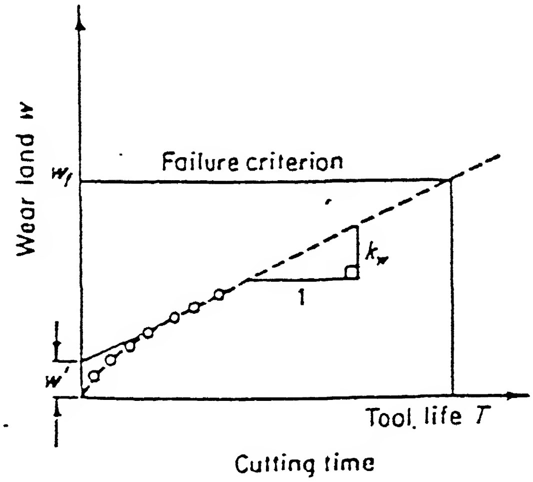

Figure 2.3: Wear-Time Curve

Where, Δw is the wear increase, w_o is the initial wear, m is the slope of the wear-time curve, and t is the cutting time.

Since increase in wear at a particular cutting time is dependent on the given cutting conditions , the wear level may be expressed as:

$$w = w_o + a_o(V^{a_1} f^{a_1} d^{a_3} t^{a_4}) \tag{2.6}$$

Where V, f and d are the cutting speed, feed and depth of cut respectively

and a_o, a_1, a_2, a_3 and a_4 are constants, dependent on the tool-work material combination.

From the experiments conducted by S.K.Choudhury and Eswar Kumar [17] the variation of force with the time can be expressed as (see Fig 2.4(a) & (b))

$$F = F_o + nt \tag{2.7}$$

Where F_o is the initial force developed at time t=0 which is purely dependent on the given cutting conditions , F is the force after a time t and n is the slope of the Force-time curve. This n is different at different values of speed, feed and depth of cut. So the equation

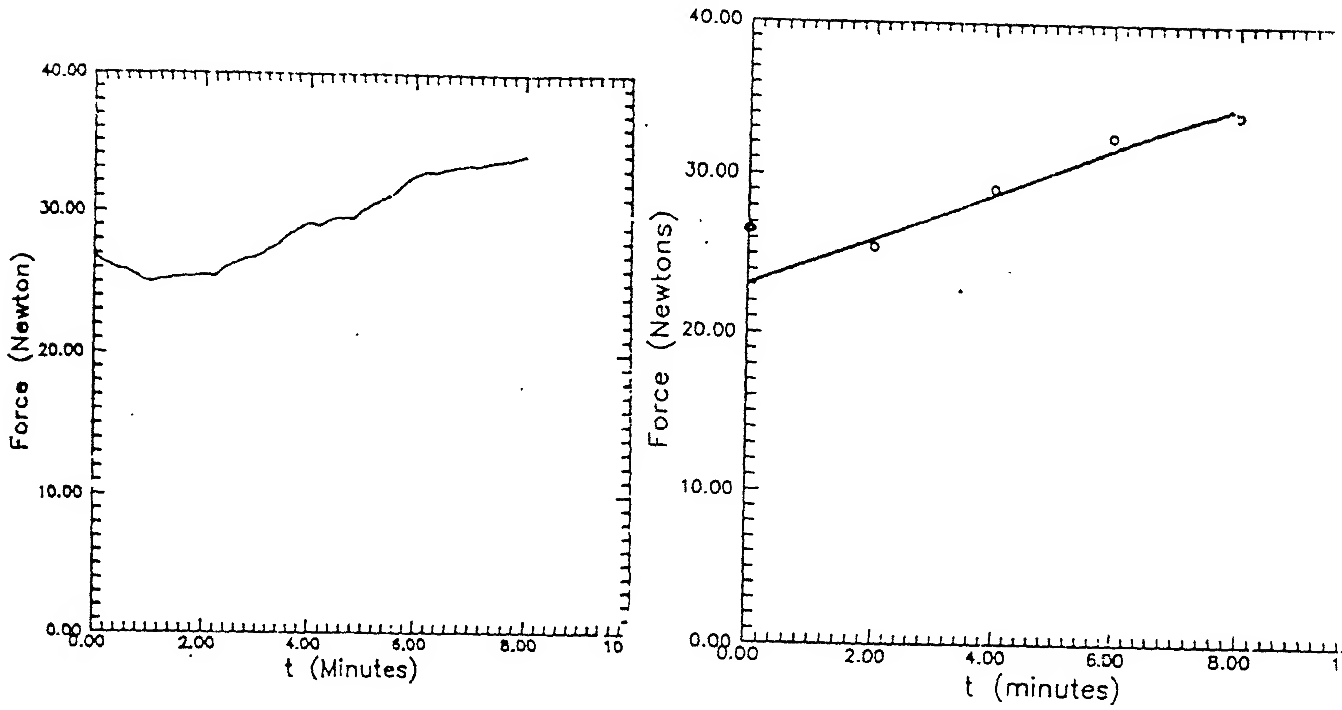

Figure 2.4: a) Variation of Force with Time b) Best Fit

(2.7) can be modified as:

$$F = F_o + b_o V^{b_1} f^{b_2} d^{b_3} t^{b_4} \tag{2.8}$$

Where b_o, b_1, b_2, b_3 and b_4 are constants, dependent on the tool-work material combination.

The time from the above equation (2.8) can be expressed as

$$t = p\left(\frac{F - F_o}{V^{b_1} f^{b_2} d^{b_3}}\right)^k \tag{2.9}$$

Where p and k are constants.

The forces acting on a cutting tool for a given work piece material depend up on a number of considerations [18] :

1. Cutting force increases with the increase in feed and depth of cut.

2. Cutting speed does not have much influence on the cutting force.

There exists an initial force when the cutting is started and it increases almost linearly with time. The initial force is dependent upon the given cutting conditions. There is a similarity between the curves shown in Fig 2.3 and 2.4. In both of the cases there is some initial value recorded and as the machining progresses both of them seem to increase gradually with time which could be assumed to be contributed by the tool wear. So it can be concluded that the variation in tool wear can be reliably estimated by measuring the variation in cutting force.

Koren[3] gives a linear relationship between the cutting or tangential force increment, ΔF and the increase in the flank wear as:

$$\Delta F = k\, h_f\, \Delta t \tag{2.10}$$

Where $k = C_p V^{b_v} f^{b_f} d^{b_d}$

C_p - Coefficient which depends on the W/P-Tool material combination.

b_v, b_f, and b_d - exponents for determination of the tangential or cutting force.

In our case, the wear increase, $h_f\, \Delta t$ is $w - w_o$

Now we can correlate the force and the tool wear from the equations (2.4) , (2.9)and (2.10) as

$$w = w_o + m \left(\frac{F - F_o}{b_o V^{b_1} f^{b_2} d^{b_3}} \right)^k \tag{2.11}$$

But the initial force developed and the initial flank wear on the tool mainly depend upon the cutting conditions which can be expressed in terms of speed, feed and depth of cut. so the equation (2.11) can be modified as

$$w = c_o V^{c_1} f^{c_2} d^{c_3} + m \left(\frac{F - p_o V^{p_1} f^{p_2} d^{p_3}}{b_o V^{b_1} f^{b_2} d^{b_3}} \right)^k \tag{2.12}$$

Where $c_o, \dots, c_3$ and $p_o, \dots, p_3$ are constants, dependent on the tool-work material combination.

After rearranging, the equation (2.12) can be written as:

$$w = a_o F^{a_1} + b_o V^{b_1} f^{b_2} d^{b_3} \tag{2.13}$$

But preliminary studies reveal that the increase in wear is also dependent upon the change in the work piece diameter. So the equation (2.13) is further modified as:

$$w = a_o F^{a_1} + b_o V^{b_1} f^{b_2} d^{b_3} D^{b_4} \tag{2.14}$$

The horizontal cutting force components (F_f, F_r) increase suddenly at the instant of breakdown of cutting edge and the vertical force seems to be most sensitive to machining instability. The two force components-the cutting force, F_c and the feed force, F_f seem to monitor the condition of the tool totally. So it is believed that these two forces should be used to predict the value of the tool wear at any instant. In order to include these two forces into our mathematical model the ratio of the feed force, F_f to cutting force, F_c is taken as one parameter.As we are taking the diameter of the work piece as one of the variables, the cutting speed, *V* can well be replaced by the *rpm* of the machine, *N*. So the tool wear can finally be expressed as:

$$w = a_o \left(\frac{F_f}{F_c}\right)^{a_1} + b_o N^{b_1} f^{b_2} d^{b_3} D^{b_4} \tag{2.15}$$

Where, F_c and F_f are cutting and feed forces

N - *rpm* of the machine, *rev/min.*

f - feed, *mm/rev*

d - depth of cut, *mm*

D - Diameter of the work piece, *mm.*

$a_o, a_1, b_o, b_1, b_2, b_3$ and b_4- Constants of the equation to be found out from the experiments.

2.3 Solution of the model

The above derived model equation (2.15) is solved to estimate the unknown constants. For this purpose the *method of least squares* to estimate the parameters is being followed. The total number of experiments to be performed is decided based on the planning of experiments presented in the next chapter.

If we represent all the input variables *viz.* force ratio, cutting speed, feed rate, depth of cut and diameter by x_1, x_2, x_3, x_4 and x_5 in the equation (2.15) then the model can be written as:

$$y = a_o x_1^{a_1} + a_2 x_2^{a_3} x_3^{a_4} x_4^{a_5} x_5^{a_6} \tag{2.16}$$

Let n be the total number of experiments then we will get n number of above equations with different values of x's and y's. In other words, the above equation (2.15) consists of observed (measured) responses y_t, known to be for corresponding k-dimensional inputs x_t. This situation may be represented by the regression equations:

$$y_t = f(x_t, a^o) + e_t \qquad t = 1, 2, ..., n \tag{2.17}$$

Where $f(x_t, a)$ is the known response function, a^o is the p-dimensional vector of unknown parameters, and e_t represent un-observable observational or experimental errors. The above set of non-linear regression equations may be written in a convenient vector form

$$y = f(a^o) + e \tag{2.18}$$

by adopting conventions namely

$$y = \begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ . \\ y_n \end{bmatrix}, f(a) = \begin{bmatrix} f(x_1, a) \\ f(x_2, a) \\ . \\ . \\ . \\ f(x_n, a) \end{bmatrix} and\, e = \begin{bmatrix} e_1 \\ e_2 \\ . \\ . \\ . \\ e_n \end{bmatrix} \tag{2.19}$$

This method choses the parameters a^o, which minimizes the sum of squares of the deviations over all observations. The sum of the squared deviations is:

$$SSE(a) = \sum_{t=1}^{n} [y_t - f(x_t, a)]^2 \tag{2.20}$$

The Gauss-Newton method is based on the substitution of a first order Taylor series approximation to *f(a)* about a trail parameter value a_T in the formula for residual sum of squares *SSE(a)*. The approximating sum of squares thus obtained is

$$SSE_T(a) = \|y - f(a_T) - F(a_T)(a - a_T)\|^2. \tag{2.21}$$

Where $F(a_T) = \frac{\partial}{\partial a'} f(a_T)$

The parameters are chosen iteratively in order to minimize the residual sum of squares. The value of the parameter minimizing the approximating sum of squares is:

$$a_M = a_T + \left[F'(a_T)F(a_T)\right]^{-1} F'(a_T)\left[y - f(a_T)\right] \tag{2.22}$$

Chapter 3

Instrumentation and Experimentation

3.1 Instrumentation

3.1.1 Dynamometer

Force measurement actually involves the measurement of a bending moment, caused by that force, with a suitable calibration between the force and the deflection it produces. For measuring small deflections, various devices have been used [6]. Some of them are listed below:

1. The Dial Indicator.
2. Pneumatic Devices.
3. Optical Devices.
4. Dynamometer based on Piezoelectric crystals.
5. Dynamometer based on Strain Gauges.

Out of these, most widely used are the strain gauge type dynamometers. In this category, bonded-wire strain gauges have commonly been used. Usually these bonded wire gauges have been specified by the resistance (R) and Gauge factor (F). the gauge factor is a measure of sensitivity of gauge and is defined as:

$$F = \frac{\Delta R/R}{\Delta l/l} = \frac{\Delta R}{\epsilon R} \tag{3.1}$$

Where,$\epsilon = \frac{\Delta l}{l}$is the normal strain.

ΔR is increment in resistance.

l is the length of the wire.

Δl is the increment in length.

In our case, bonded strain gauge of resistance 120$\Omega$and gauge factor 2, have been used. In order to measure strains of the order of $1\mu m/m$,the changes of the resistances of the same order of magnitude need to be measured. This can be made by means of a Wheatstone bridge as shown in Fig. 3.1. No current will flow through the galvanometer (G) if the four resistances, $C_1, C_2, T_1,$ and T_2 satisfy the equation

$$\frac{C_1}{T_2} = \frac{T_1}{C_2} \tag{3.2}$$

For the sake of simplicity, the lathe operation is frequently taken as an orthogonal cutting process [19]. In this case, the resultant force will act in a known plane and only two forces are required to analyze the cutting process. A schematic digram of the dynamometer used in present work is shown in the Fig.3.2.

In the present case, the axial cutting force F_c and tangential force F_f have been measured. It is apparent that F_c will cause a bending moment M_c at a distance, r, and F_f will cause a bending moment, M_f , as

$$M_c = F_c r \tag{3.3}$$

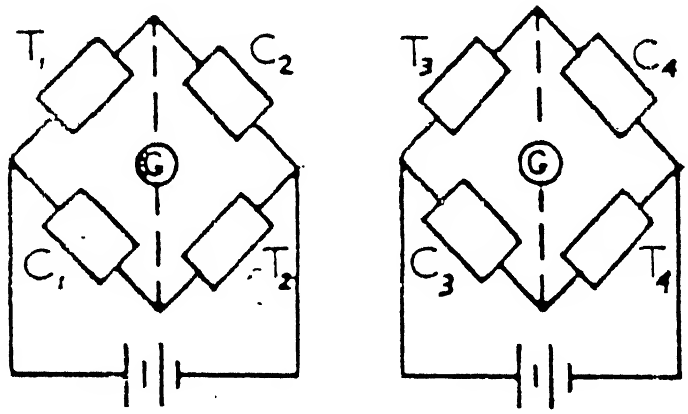

Figure 3.1: a)Wheatstone bridge for F_c b)Wheatstone bridge For F_f

$$M_f = F_f r \tag{3.4}$$

A two component cutting force dynamometer of cantilever type is used in the present work. The design of the dynamometer is illustrated in Fig 3.3. The dynamometer structure is made of aluminium. The action of forces is to bend the structure. The axial cutting force F_c bends the structure about the axis A-A and the tangential feed force F_f bends the structure about the axis B-B. Strain gauges were used to measure these moments, and the recordings are calibrated to give a measure of forces applied. Strain gauges were cemented with gaging wires parallel to the dynamometer axis O-O. the free end of the dynamometer structure has a square section into which the tool is inserted as shown in the Fig. 3.3.

To measure the moment M_c due to the cutting force F_c, two gauges T_1 and T_2 are cemented to the top of the measuring section, and two more gauges C_1 and C_2 are cemented directly below them. Thus when the force is applied, two gauges T_1 and T_2 are subjected to tension, while the two others, C_1 and C_2 receive an equal amount of compression, there by satisfying requirements for a complete Wheatstone bridge as shown in Fig 3.1. In a similar manner the moment M_f due to feed force F_f is measured by four gauges, T_3, T_4, C_3 and C_4, which are cemented as shown in Fig 3.3.

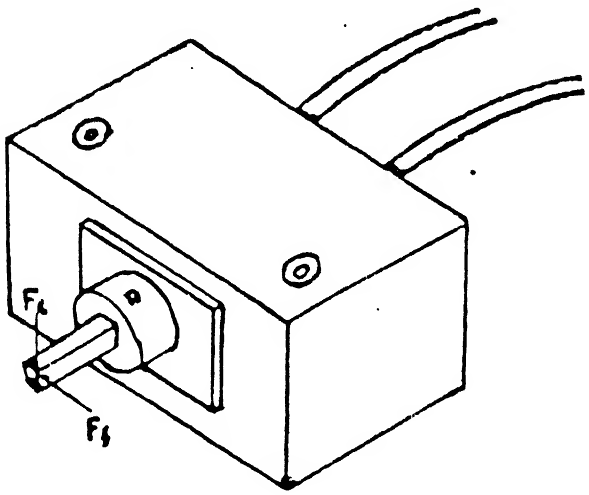

Figure 3.2: Dynamometer used in the Present work

3.1.2 Recording of Forces

For the measurement of the cutting force F_c all the four strain gauges T_1, T_2, C_1, and C_2 are connected in the Wheatstone bridge as shown in the figure Fig.3.1. A potentiometer is connected across one of the four resistances. The recorder is connected in the place of the galvanometer.The power supply is given as shown in the figure Fig.3.1. The resistance in the potentiometer is varied until the Wheatstone bridge is balanced. In other terms, the resistance is varied until no current passes through the recorder. When the current passing through the recorder equals zero, the pen which records the changes in the resistances comes to a stand still. Then this dynamometer set-up with the inserted tool is put in to the cutting operation. Once the cutting process starts, the cutting force F_c acts on the tool which in turn deforms the strain-gauges T_1, T_2, C_1, and C_2. As a result of this deformation their resistances are changed which create an imbalance in the Wheatstone bridge. And because of this imbalance the current flows through the recorder. Recorder pens plot the variation of the resistances (cutting force) with respect to time. As the recorder is already calibrated using some static loads, the (variation in the resistances) cutting force can be easily quantified using the values in the plots. In a similar manner the feed force F_f can be measured.

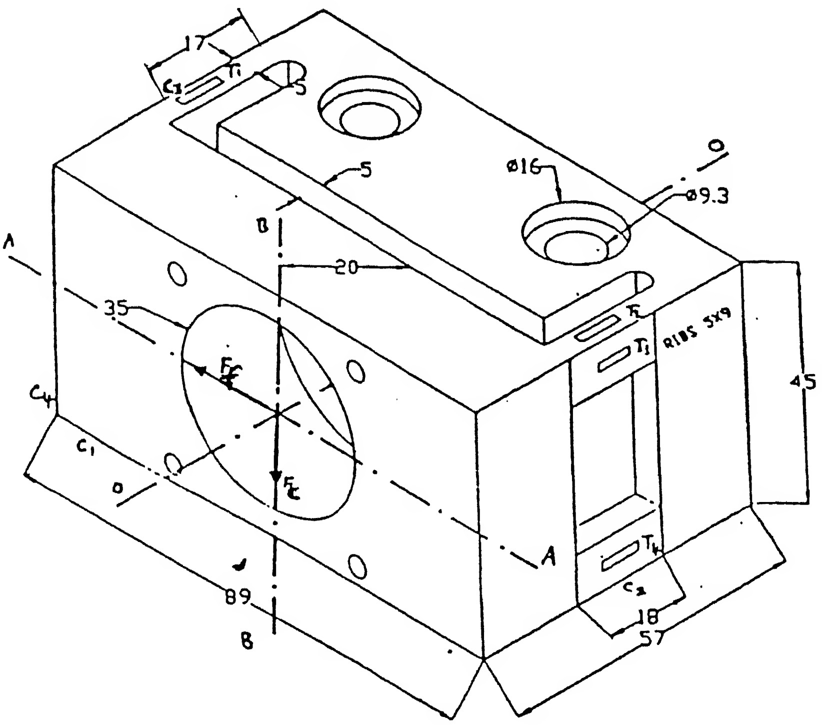

Figure 3.3: Schematic Diagram of a Two-Component Strain gauge Dynamometer

3.2 Planning of Experiments

A scientific approach for planning the experiments must be employed, when an experiment is to be performed most efficiently. When the problem involves data that are subjected to experimental errors, statistical methodology is the only alternative to the analysis.

Planning of experiments is introduced to fulfill the following requirements:

- ► To get the data, uniformly from all the regions of the working area.
- ► To reduce the total number of experiments.
- ► To determine the effects of the input parameters on the process output.

The flowchart for the present scheme is given in Fig. 3.4. If all the factors represent the quantitative variables like temperature, time, speed *etc.*, the response, y can be written as a

function of the levels of these variables [20].

$$y_u = \phi(x_{1u}, x_{2u}, ..., x_{ku}, \theta_{1u}, \theta_{2u}, ..., \theta_{nu}) + e_u \tag{3.5}$$

Where, u=1,2,...,N

N is the total number of observations in a particular experiment.

x_{iu}=the level of i_{th} factor in the u_{th} observation

$\theta_{1u}, \theta_{2u}, ...\theta_{nu}$=constants in the u_{th} observation

e_u=experimental error of the u_{th} observation

and, function ϕ is the response surface

A knowledge of function ϕ, gives a complete summary of the results of experiments. This experimental design can be developed for fitting the polynomials of first or second order.

When different factors influence the character under study, it is always desirable to test different combinations of factors at various levels. Such experiments are called *Factorial Experiments* and are widely used because of the wider inductive basis of the conclusion drawn from them and of estimating interactions between different factors.

Many experiments involve a study of effects of two or more factors. It can be shown that, in general, factorial designs are most efficient for this type of experiment. By a factorial design, it is meant that in each complete trial or replication of the experiment, all possible combinations of the levels of the factors are investigated.

The effect of a factor is defined to be the change in response produced by a change in level of factor. This is frequently called a *main effect* because it refers to the primary factors of interest in the experiment. In some experiments, the difference in response between the levels of one factor is not the same at all levels of the other factors. When this occurs, there is an *interaction* between the factors. Factorial designs are preferred because they are more efficient than one-factor-at-a-time experiments.

3.2.1 3^k Factorial Design for three factors

Out of all the factorial designs 3^k*factorial design* is the widely used one for developing non-linear mathematical models. In this design three levels are considered for each factor. The total number of experiments to be performed depends upon the number of factors, *k*.

Now suppose there are three factors (*A*, *B*, and *C*) under study, and each factor is at three levels (0, 1, and 2) arranged in a factorial experiment. This is a 3^3 *factorial design,* and the experimental layout and treatment combination notation are shown in Fig. 3.5. The 27 treatment combinations have 26 degrees of freedom. Each *main effect* has 2 degrees of freedom, each two-factor *interaction* has 4 degrees of freedom, and the three-factor *interaction* has 8 degrees of freedom [21].

In the present case the total number of input cutting parameters (factors) is three *viz.* cutting speed, feed rate and depth of cut. So the 3^3 *factorial design* is implemented. All the three levels of the factors are decided, on the basis of data given in hand books, machine capabilities and the past experience. These three levels for the three factors are given in table Tab.4.1. According to this design, to determine all possible *main effects* as well as *interactions* of all the factors on the character under study, 3^3 number of experiments have to be conducted in total. In order to reduce the cost of experiments no replicates (repetitions) are done. So the total number of experiments has been decided as twenty seven.

3.3 Experimental Setup and Procedure

The experimental set-up mainly consists of Lathe, a Dynamometer and a Recorder. The cutting tool is inserted in to the dynamometer. A schematic diagram of the experimental set-up is shown in Fig. 3.6.

To obtain experimental database, which can be used to build mathematical models of the force-wear characteristics, having statistical significance over a specified operating domain, it is necessary to design the experimental procedure accordingly. HSS cutting tools are clamped to a two-component strain-gauge dynamometer. These tools are used are used to cut C45 steel work piece of 600*mm* length, using an engine lathe. Before carrying out the

experiments, first of all the machine tool (an engine lathe for our purpose)and the cutting tool with certain geometry have been selected. For the measurement of force components, a force dynamometer is used, schematic diagram of which is shown in Fig. 3.2. To correlate the output signal with the force acting on the tool, the dynamometer was calibrated before carrying out the actual experiments. For calibration purpose, the selected cutting tool is inserted into the hole of the dynamometer, keeping certain amount of tool overhang. This overhang must be kept constant throughout the experiments. Now, the Wheatstone bridge of the dynamometer is made balanced by appropriately adjusting the various arms of the bridge. The over-hanged cutting tool has been loaded increasingly with known weights and corresponding deflections have been noted down. The weights are then, unloaded in the similar fashion, in the same steps and corresponding deflections have been noted down. The average of weights, while in loading and unloading; and the average corresponding deflection has been used for calibrating the dynamometer. The force components can be recorded by connecting the output of the dynamometer to the recorder, which is explained in detail in the subsection **3.1.2.**

For carrying out the experiments, the workpiece was held in a four jaw chuck and supported by a center in the tail-stock. Tool height and tool overhang were set to the required level with the help of gauges. The bridge circuits for measuring the forces were balanced to give zero initial reading with the help of a potentiometer. A rough turning pass was made to eliminate the runout of the workpiece. Then the actual experiments were carried out with the different input cutting conditions for different experiments. The output flank wear-land, *w,* was measured with a tool-room microscope having graduation marked on the eye-piece.

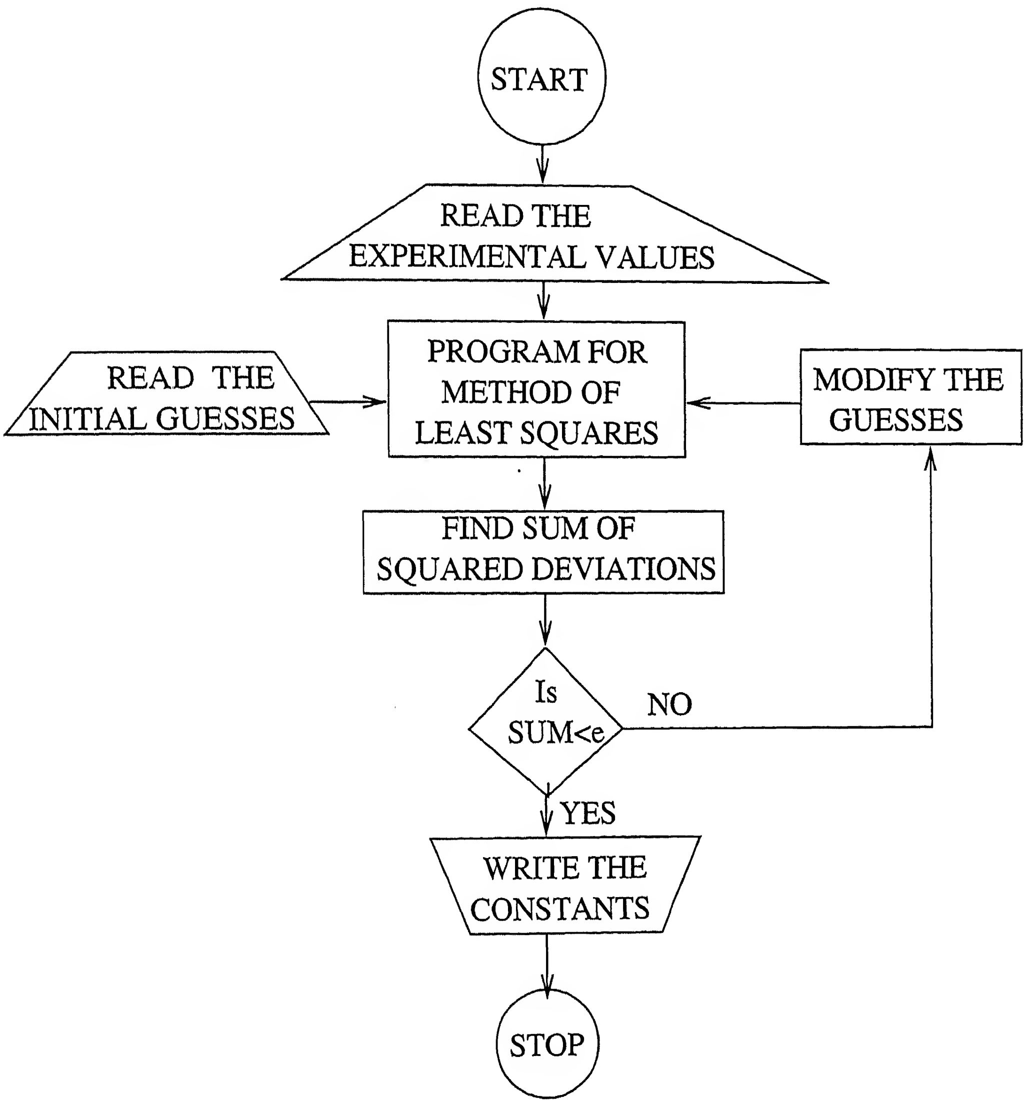

Figure 3.4: Flow chart of the scheme

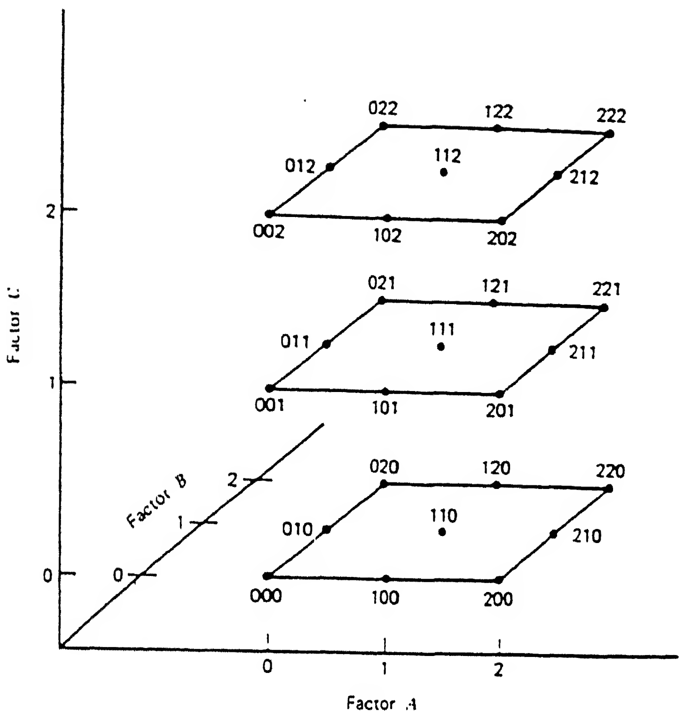

Figure 3.5: Treatment combinations in a 3^3 design.

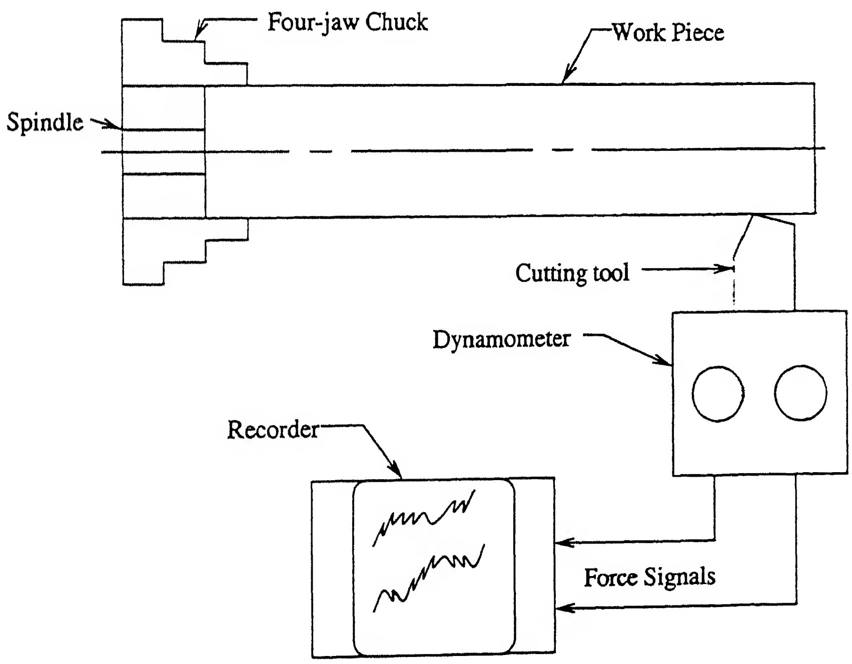

Figure 3.6: Schematic Diagram of the set-up

Chapter 4

Results and Discussion

4.1 Experimentation

The experiments were carried out as discussed in **Chapter 3.** For the experiments C45 steel was used as the workpiece material and HSS with 10% Cobolt as cutting tool material. The material composition and the tool geometry are given in the **Appendix.** An engine lathe, with the specifications given in the **Appendix,** was used as the machine tool. The tool geometry, tool overhang, and the tool height, were set with the help of gauges and maintained uniformly for all the experiments. The range of input cutting parameters was decided, on the basis of data given in hand books for this particular tool-work combination, machine capabilities and the practical experience as:

* Spindle rotation : 90-160 *rpm.*

* Feed rate : 0.1-0.2 *mm/rev.*

* Depth of cut : 0.5-1.5 *mm.*

To reduce the total number of experiments and to get the data uniformly from all the regions of the selected working area, the design of experiments procedure was adopted. In the present case 3^k *Factorial design for three factors* has been implemented. The input parametric values were scaled, according to the three levels which are given in the Tab. 4.1.

Parameters Levels	Cutting Speed *(rpm)*	Feed rate *(mm/rev)*	Depth of cut *(mm)*
1	90	0.125	0.5
2	114	0.150	1.0
3	142	0.175	1.5

Table 4.1: Different Levels of Cutting Parameters

A total number of twenty seven experiments were carried out which were used to develop the mathematical model. The set of input cutting conditions and the output responses along with the corresponding force ratio and the diameter given in Tab. 4.2 have been supplied to the computer program written in the *"C"* language to solve the regression equation.

In order to find the unknown parameters of the equation (2.15), the *method of least squares* was used in the present work. The initial guesses are given to the program and the program is run for 30 iterations. The allowable error of 0.0000001 (sum of squared deviations) is used and the system took 13 iterations to minimize the error to nearly zero. The values of various constants in the equation (2.15) are obtained as:

$a_o = 0.344$

$a_1 = 0.611$

$b_o = 0.000001$

$b_1 = 1.709$

$b_2 = 0.928$

$b_3 = 1.151$

$b_4 = 1.031$

So the mathematical model (regression equation) of force-wear characteristics can be stated as :

$$w = 0.344\left(\frac{F_f}{F_c}\right)^{0.611} + 0.000001N^{1.709}f^{0.928}d^{1.151}D^{1.031} \tag{4.1}$$

4.2 Validation of model

Once the mathematical model (regression equation) is developed, the input parameters *viz.* force ratio, cutting speed, feed rate, depth of cut and diameter are fed to the equation and the output variable, tool wear is predicted for each of the twenty seven experiments. A plot is drawn between the measured tool wear and the calculated tool wear with the measured flank wear on the X-axis and the calculated flank wear on the Y-axis as shown in Fig. 4.1.

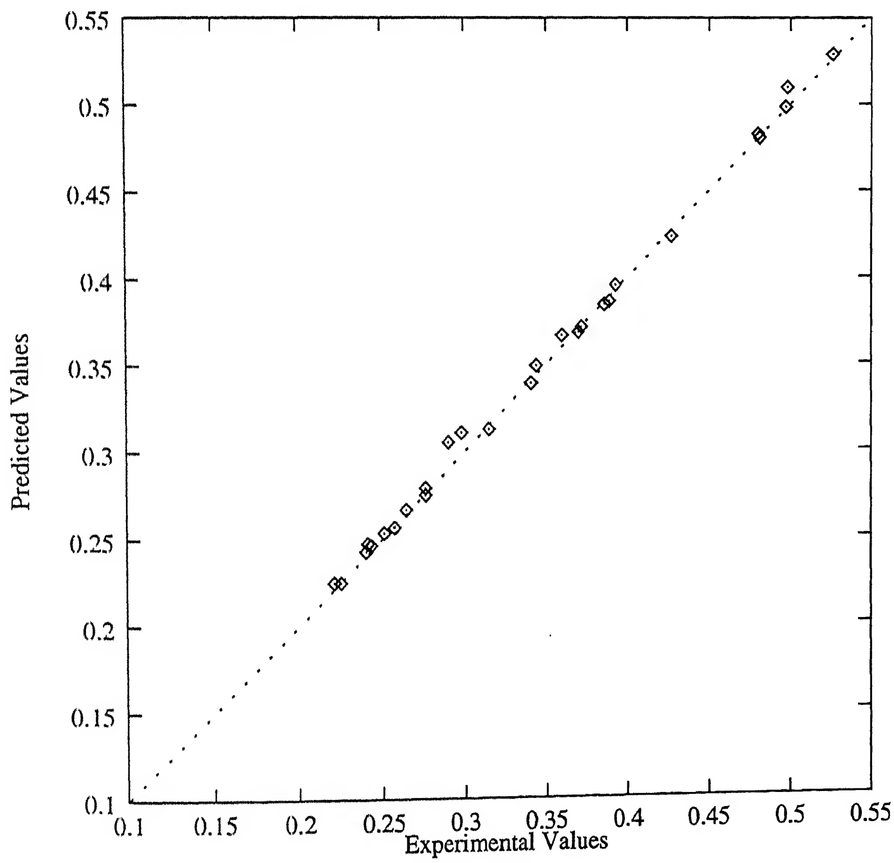

Figure 4.1: Experimental Vs Predicted Values of Flank Wear

There appears a good correlation between these two sets of values. In the scatter diagram all the points nearly fall on a 45^o line which means that the predicted and the experimental values are very close for all the twenty seven experiments.

The correlation co-efficient between the experimental values and the predicted values has been found out to be 0.9984. Thus it can be stated that our developed model predicts the values of the flank wear reliably over the selected range of input cutting parameters .

4.3 Effect of various parameters

For studying the effect of given input parameters on the flank wear, the regression equation is reduced with only two parameters *viz.* the output parameter-flank wear and one of the input parameters, the effect of which on the output parameter has to be established. This is done by assigning an optimum constant value to all other input parameters at which the flank wear is minimum. The optimum value for a particular parameter is selected from the Tab.4.2 within it's working range. After getting the reduced equation, the values of flank wear over a range of values of input parameter were calculated. plots are drawn between these values of tool wear and the values of parameters individually, with the corresponding parameter on the X-axis and flank wear on the Y-axis. The various plots obtained are shown in Fig.4.2- Fig.4.6.

In all the plots it is clear that by increasing feed, depth of cut, diameter, force ratio and speed, the flank wear increases. Flank wear increases almost linearly with the feed rate, depth of cut and diameter. It is evident from the corresponding reduced regression equations. In the case of feed rate, depth of cut and diameter, we get a reduced equation in the form of equation 4.2 with the exponent of x approaching one, which is almost linear. Natures of these curves are shown in figures Fig.4.2, Fig.4.3 and Fig.4.5 respectively.

$$y = mx^a + c \tag{4.2}$$

In the case of speed and force ratio, we get almost a parabolic equation with exponent of x as 1.71 and 0.61 respectively.Natures of these curves are shown in figures Fig.4.5 and

Parameters Levels	Cutting Speed *(rpm)*	Feed rate *(mm/rev)*	Depth of cut *(mm)*
1	90	0.125	0.5
2	114	0.150	1.0
3	142	0.175	1.5

Table 4.1: Different Levels of Cutting Parameters

A total number of twenty seven experiments were carried out of which fifteen randomly selected values were used to develop the mathematical model. The set of input cutting conditions and the output responses along with the corresponding force ratio and the diameter given in Tab. 4.2 have been supplied to the computer program written in the "*C*" language to solve the regression equation.

In order to find the unknown parameters of the equation (2.15), the *method of least squares* was used in the present work. The initial guesses are given to the program and the program is run for 30 iterations. The allowable error of 0.0000001 (sum of squared deviations) is used and the system took 13 iterations to minimize the error to nearly zero. The values of various constants in the equation (2.15) are obtained as:

$a_o = 0.324$

$a_1 = 0.601$

$b_o = 0.000003$

$b_1 = 1.623$

$b_2 = 0.912$

$b_3 = 1.162$

$b_4 = 1.01$

So the mathematical model (regression equation) of force-wear characteristics can be stated as :

$$w = 0.324\left(\frac{F_f}{F_c}\right)^{0.601} + 0.000003N^{1.623}f^{0.912}d^{1.162}D^{1.01} \qquad (4.1)$$

4.2 Validation of model

Once the mathematical model (regression equation) is developed, the input parameters *viz.* force ratio, cutting speed, feed rate, depth of cut and diameter are fed to the equation and the output variable, tool wear is predicted for each of the twenty seven experiments. A plot is drawn between the measured tool wear and the calculated tool wear for the remaining twelve experimental values with the measured flank wear on the X-axis and the calculated flank wear on the Y-axis as shown in Fig. 4.1.

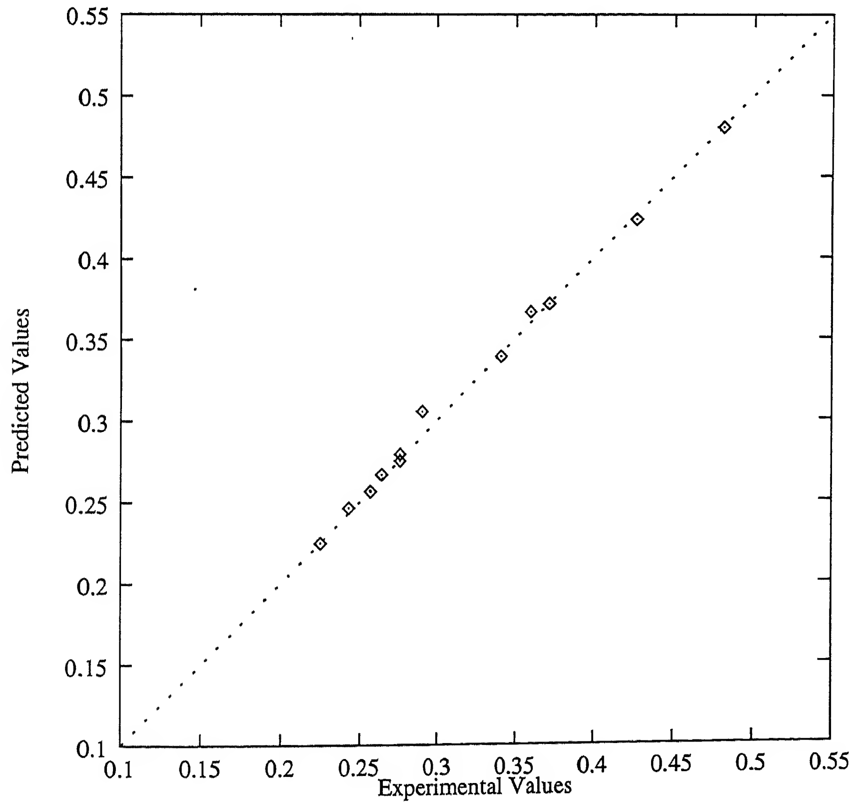

Figure 4.1: Experimental Vs Predicted Values of Flank Wear

There appears a good correlation between these two sets of values. In the scatter diagram all the points nearly fall on a 45^o line which means that the predicted and the experimental values are very close for all the twelve experiments.

The correlation co-efficient between the experimental values and the predicted values has been found out to be 0.9984. Thus it can be stated that our developed model predicts the values of the flank wear reliably over the selected range of input cutting parameters .

4.3 Effect of various parameters

For studying the effect of given input parameters on the flank wear, the regression equation is reduced with only two parameters *viz.* the output parameter-flank wear and one of the input parameters, the effect of which on the output parameter has to be established. This is done by assigning an optimum constant value to all other input parameters at which the flank wear is minimum. The optimum value for a particular parameter is selected from the Tab.4.2 within it's working range. After getting the reduced equation, the values of flank wear over a range of values of input parameter were calculated. plots are drawn between these values of tool wear and the values of parameters individually, with the corresponding parameter on the X-axis and flank wear on the Y-axis. The various plots obtained are shown in Fig.4.2- Fig.4.6.

In all the plots it is clear that by increasing feed, depth of cut, diameter, force ratio and speed, the flank wear increases. Flank wear increases almost linearly with the feed rate, depth of cut and diameter. It is evident from the corresponding reduced regression equations. In the case of feed rate, depth of cut and diameter, we get a reduced equation in the form of equation 4.2 with the exponent of x approaching one, which is almost linear. Natures of these curves are shown in figures Fig.4.2, Fig.4.3 and Fig.4.5 respectively.

$$y = mx^a + c \tag{4.2}$$

In the case of speed and force ratio, we get almost a parabolic equation with exponent of x as 1.62 and 0.6 respectively.Natures of these curves are shown in figures Fig.4.5 and

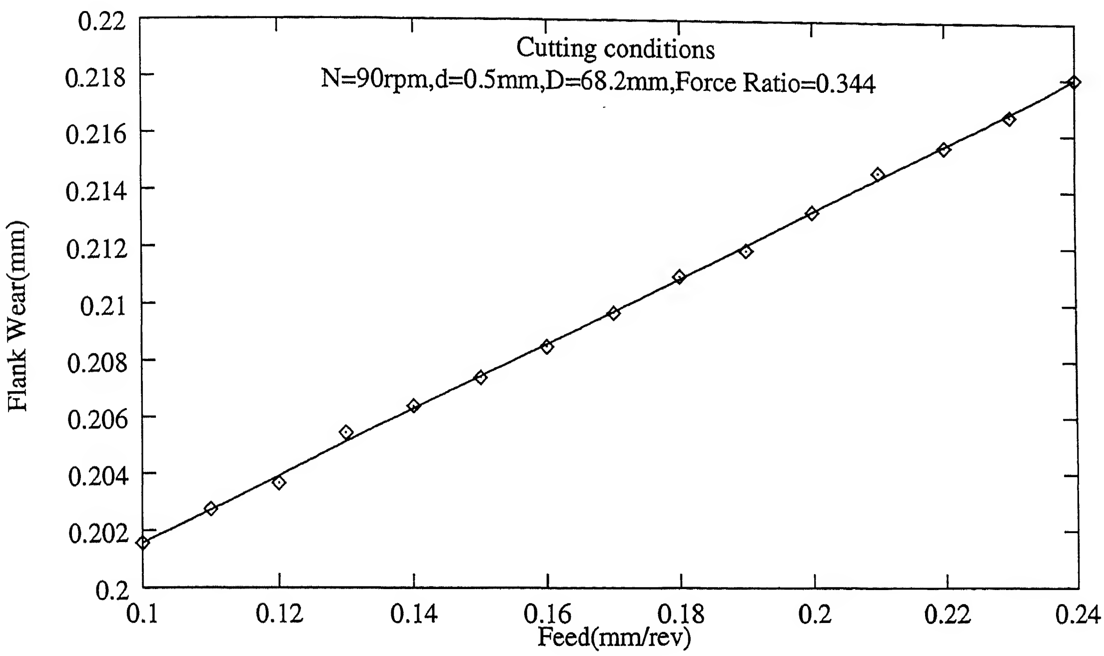

Figure 4.2: Flank Wear Vs Feed rate

Fig.4.6 respectively.

Out of all the parameters effecting flank wear, the cutting speed (velocity) appears to be effecting more which re-confirms the one already concluded in the literature. The parameter *force ratio* also seems to be effecting the tool wear significantly, which is the objective of the present work. So force ratio seems to reliably monitor the tool wear.

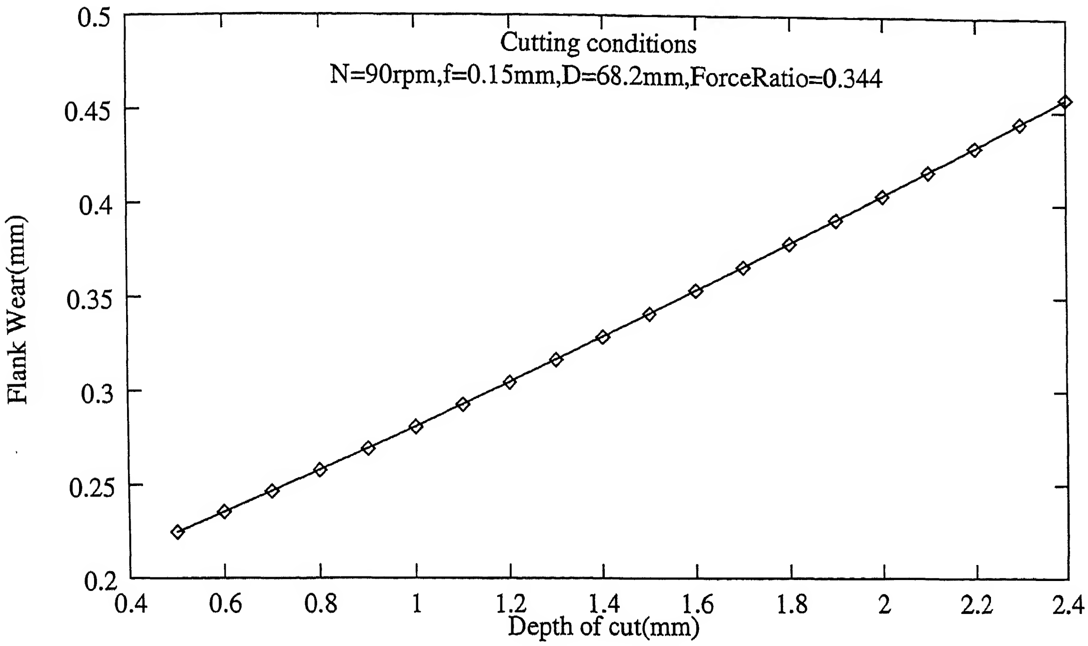

Figure 4.3: Flank Wear Vs Depth of cut

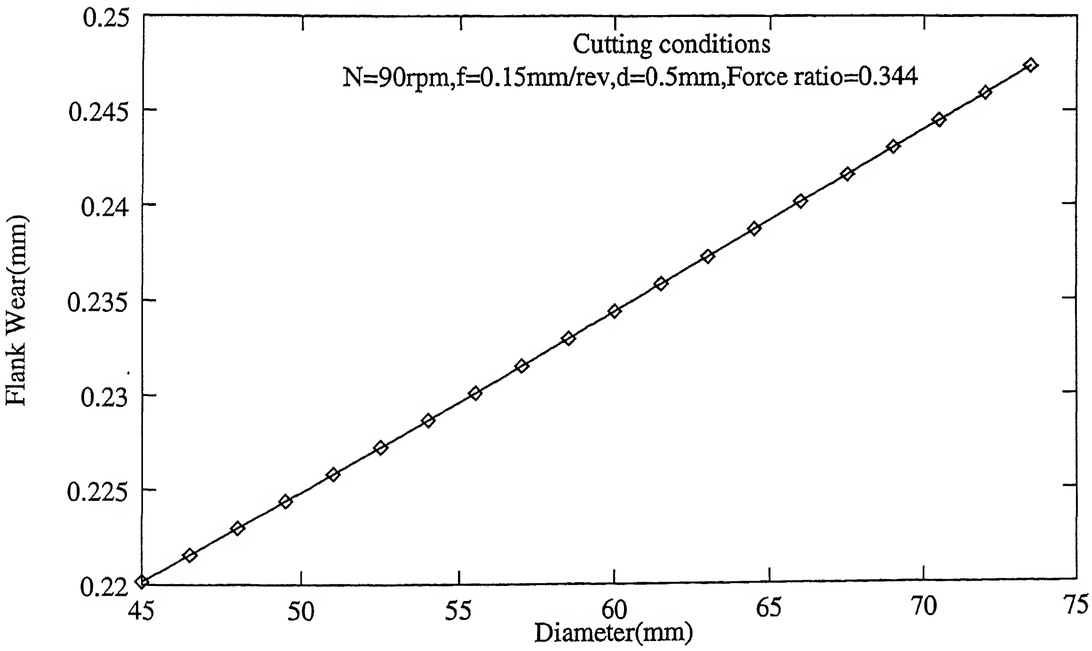

Figure 4.4: Flank Wear Vs Diameter

Expt. No.	Cutting Speed (*rpm*)	Feed rate (*mm/rev*)	Depth of cut (*mm*)	Diameter (*mm*)	Force Ratio	Tool Wear Measured (*mm*)	Tool Wear Calculated (*mm*)
1	90	0.125	0.5	42.3	0.458	0.243	0.246285
*2	90	0.125	1.0	73.2	0.481	0.344	0.349314
*3	90	0.125	1.5	71.2	0.359	0.386	0.384637
4	90	0.150	0.5	68.2	0.344	0.225	0.224782
*5	90	0.150	1.0	67.0	0.450	0.298	0.310761
6	90	0.150	1.5	71.2	0.315	0.341	0.339202
*7	90	0.175	0.5	43.3	0.413	0.226	0.224931
8	90	0.175	1.0	62.5	0.408	0.276	0.279168
*9	90	0.175	1.5	65.0	0.344	0.315	0.312714
10	142	0.125	0.5	45.3	0.344	0.257	0.256455
*11	142	0.125	1.0	47.2	0.469	0.393	0.395814
*12	142	0.125	1.5	50.3	0.493	0.526	0.528748
*13	142	0.150	0.5	51.3	0.344	0.251	0.253352
14	142	0.150	1.0	53.3	0.412	0.372	0.371658
*15	142	0.150	1.5	56.3	0.481	0.498	0.509644
16	142	0.175	0.5	44.3	0.481	0.276	0.275023
17	142	0.175	1.0	58.3	0.424	0.360	0.366718
18	142	0.175	1.5	60.5	0.446	0.481	0.480427
19	114	0.125	0.5	61.1	0.393	0.264	0.266688
*20	114	0.125	1.0	63.2	0.481	0.389	0.386477
*21	114	0.125	1.5	66.2	0.479	0.497	0.498206
*22	114	0.150	0.5	55.1	0.387	0.241	0.247351
*23	114	0.150	1.0	60.1	0.537	0.370	0.368612
*24	114	0.150	1.5	72.4	0.497	0.480	0.482535
*25	114	0.175	0.5	56.1	0.393	0.240	0.242715
26	114	0.175	1.0	58.1	0.391	0.290	0.305380
27	114	0.175	1.5	69.3	0.446	0.427	0.423771

Table 4.2: Experimental Data

* Values used for the development of model.

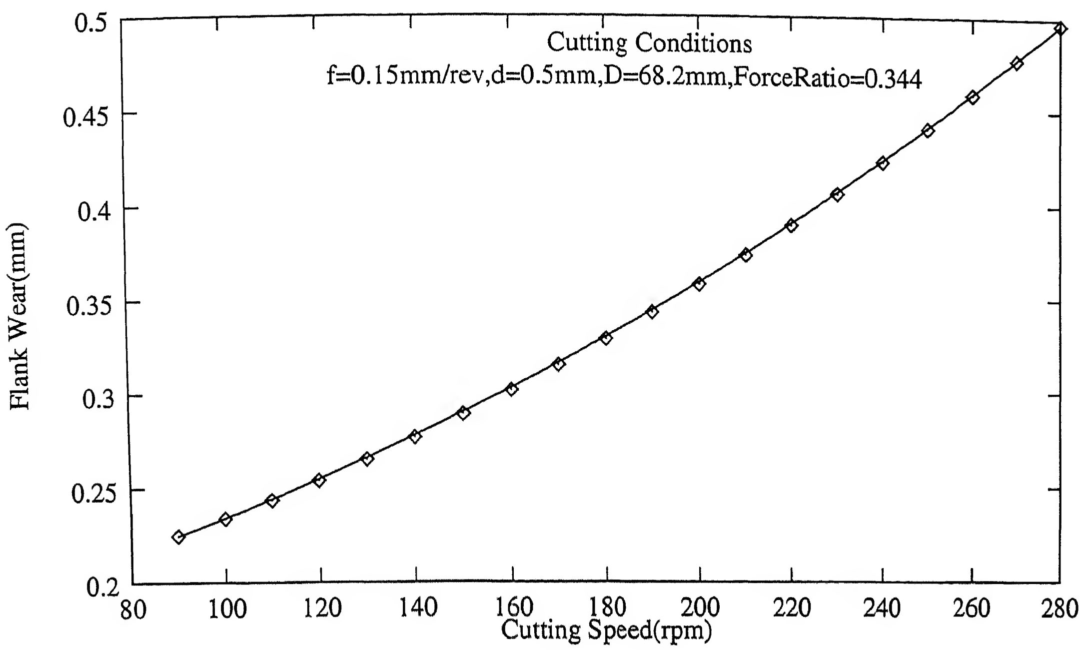

Figure 4.5: Flank Wear Vs Speed

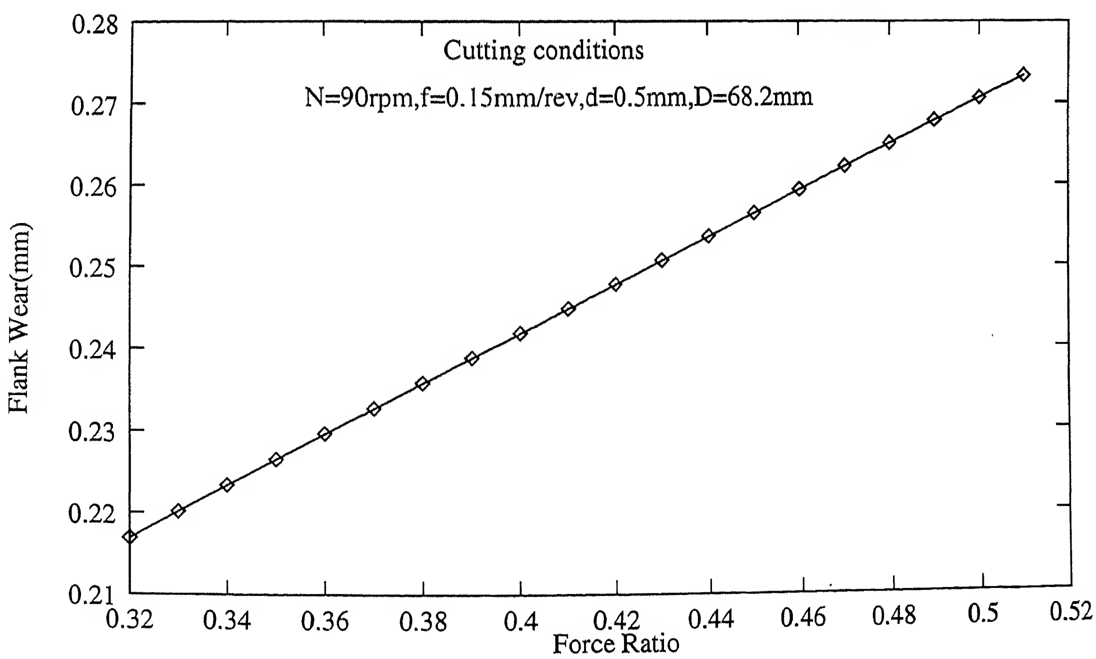

Figure 4.6: Flank Wear Vs Force Ratio

Chapter 5

Conclusion

5.1 Conclusions

The basic aim of on-line tool wear monitoring has been fulfilled. In the present work, a mathematical model has been developed. The flank wear can be found out on-line by measuring some easily measurable quantity, the ratio of the Feed force F_f to the Cutting force F_c.

The following objectives have been achieved:

1. For on-line monitoring of tool wear, a mathematical model has been developed correlating the ratio feed force F_f to cutting force F_c and the flank wear height.
2. For collection of the experimental data in order to develop mathematical model, a special design, *viz.*, "3^k Factorial Design" had been successfully used.
3. By comparing the experimental values and the predicted values a good agreement has been achieved between them. The developed model can be used for predicting flank wear.
4. The effect of various factors on the tool wear has been studied independently using the developed mathematical model. Flank wear increases almost linearly with the

feed rate, depth of cut and diameter. The force ratio (F_f/F_c) seems to monitor the flank wear reliably.

5.2 Scope for Future Work

The following perspective areas have been identified for the future work:

- Some more parameters which effect the tool wear can be explored to include in the model.
- For collection of experimental data a different design can be tried out.
- The mathematical model using Force ratio can be developed for other conventional processes with single/multi point cutting tools such as, Milling, Drilling, Shaping *etc.*
- As an extension of the present work, an Adaptive Control of the Turning process can be done using the mathematical model developed.
- The present developed system can also be checked for large number of experimental data to minimize the experimental error further.

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Appendix

Specifications of Equipment

Specifications

Workpiece material	: S45C steel
Workpiece composition	:0.6-0.9% Mn; 1.3-1.8% Ni; 0.055% (max) P; 0.055% (max) S; 0.05-0.35% Si; rest is iron.
Workpiece hardness	: 260 BHN.
Cutting tool material	: HSS with 5% Cobalt.
Cutting tool composition	: 18% W, 4% Cr, 2% V, 5% Co.
Cutting tool geometry	: 5-10-5-6-12-12-0*mm*.
Specifications of Lathe	: Type : LB17. center height : 170 *mm*. center distance : 1000 *mm*.

	swing over bed	: 350 *mm.*
	swing over cross slide	: 170 *mm.*
	spindle speeds	: 45-2000 *rpm.*
	feeds	: 0.0005-1.4 *mm/rev.*

Specifications of Recorder	: Pens	: Disposable fiber tip
	Pen lift	: Manual
	Weight	: Averages 22 pounds (10kg)
	Power	: 115/230 V AC ±10% 50-60 Hz, 70 volt-amperes on two pens.
	Storage	: -10 to 60°C, 0-100% relative humidity at 30°C dry bulb.

Specifications of Microscope	:Micrometer accuracy	: 0.00254mm
	Stage size	: 127mm X 127mm
	Degrees of freedom	: 3
	Co-ordinate movement mechanism	